Final Report

Grant Number: F49620-95-1-0092

STUDIES ON HIGH PRESSURE AND UNSTEADY FLAME PHENOMENA

Submitted By:

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For Consideration By:

Dr. Julian M. Tishkoff
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SUMMARY/OVERVIEW

The objective of the present program was to study the structure and response of laminar premixed and nonpremixed flames with emphases on effects of high pressure, flame/flow unsteadiness, and chemistry. The investigations were conducted through laser-based experimentation, computational simulation with detailed chemistry and transport descriptions, and advanced mathematical analysis. Phenomena studied include the steady-state structure, burning rate, and extinction of flames, the response to impulsive and periodic flow field strain rate variations, the development of intrinsic flamefront pulsating instability and its relation to extinction, and studies related to the development of detailed and simplified chemical kinetic mechanisms.

Specifically, the results show that when subjected to forced oscillation, the structure of a planar stretched premixed flame is minimally affected for all frequencies, while that of a diffusion flame is unaffected only at high frequencies. At low frequencies its thickness scales inversely with the square root of the stretch rate. It was further shown that the heat release is in phase with the imposed stretch rate for Le>1 flames and out of phase otherwise, and that at high frequencies extinction is either delayed or inhibited.

In terms of intrinsic oscillation, it was found for rich hydrogen/air premixed flames that pulsating instability and subsequently pulsation-induced extinction are triggered before the state of the flammability limit based on steady flame behavior, and as such the flammable region is reduced. The instability boundary was also found to be well described by the Sivashinsky criterion.

Studies on combustion chemistry led to the identification of a correlation between the sooting limit of diffusion flames with the peak acetylene concentration, and the establishment of an extensively-validated augmented reduced kinetic mechanism for methane oxidation which has been progressively gaining recognition and acceptance in the simulation of turbulent flames and combustors.

These results are expected to be useful to the general interests of AFOSR in the fundamental and practical issues of flame dynamics and chemical kinetics, turbulent combustion, soot formation, radiative hear transfer, flame extinction, stabilization, flammability, and supersonic combustion.

ACCOMPLISHMENT

Highlights of the accomplishments can be found in the annual reports submitted to the program director, as well as the journal papers which have appeared in print. Thus only a very brief summary of these works are mentioned in the following.

Unsteady Flames

The study of unsteady flames can be considered from three aspects of unsteadiness. The first is the response of a flame when it is subjected to an externally-applied unsteady perturbation. An example is the influence of the fluctuating flow field generated by turbulent eddies on the flame structure and the propensity for the flame to extinguish. The second is the development of intrinsic pulsating instability and the subsequent behavior of such a flame. The third is the coupling between the externally applied oscillation on an intrinsically-pulsating flame, with the possibility of resonance. During the reporting period the effects of forced oscillation were extensively studied, while fairly good understanding on intrinsic oscillation was also obtained. The coupled effects of forced and natural oscillations will be studied soon.

Regarding forced oscillation (Publications No. 1 to 5), it is first noted that when a flame is subjected to an unsteady stretch rate, a finite response time is needed for the flame to adjust. If the unsteadiness is oscillatory, the ability to adjust then depends on the oscillation frequency. Specifically, for low-frequency oscillations for which the characteristic oscillation time exceeds that of the flame time, the flame should respond quasi-steadily. However, for high-frequency oscillations, the flame does not have enough time to respond before the perturbation reverses direction, and as such the flame response loses its sensitivity to the imposed unsteadiness.

Based on the above considerations, it is therefore expected that the structure of a stretched *premixed* flame should be very insensitive to the frequency of the oscillation: at low frequencies it resembles that of the stationary stretched flame and hence is almost invariant to stretch rate variations, while at high frequencies it loses its sensitivity to oscillation anyway. Computational simulation of near-equidiffusive counterflow flames showed that there is minimum change in the flame thickness, and hence the flame structure, for oscillations over an extensive range of frequencies.

The effects of nonequidiffusion on premixed flames are manifested for low-frequency oscillations. Of particular interest is the phase relation between the imposed stretch rate and the flame temperature and thereby the heat release rate. Since the flame temperature increases for Le<1 flames and decreases otherwise, the heat release

rate is in phase with the imposed stretch rate for Le<1 flames, but is out of phase for Le>1 flames. These results could have interesting implications in combustion instability in combustion chambers.

For *diffusion* flames, since they are constrained by the counter-diffusion of fuel and oxidizer, they do not have the flexibility of premixed flames to move around. Consequently, the characteristic flame time is that of the flow time, which in the case of the counterflow flame is simply the stretch rate κ. Scaling consideration then shows that the flame thickness should vary inversely with $\kappa^{1/2}$. For flames subjected to an oscillatory stretch, the flame thickness should then scale inversely with $\kappa^{1/2}$ for low frequencies, but remain insensitive to the oscillation for high frequencies.

Regarding extinction of an oscillated flame, it is reasonable to anticipate that at low frequencies, a steadily burning flame would extinguish in the first cycle of an oscillation whose perturbation amplitude exceeds the steady-state extinction strain rate, while at high frequencies extinction is delayed or even inhibited.

Regarding intrinsic flamefront unsteadiness, the primary interest here is the relation of flamefront instability to flame extinction. Experimentally, it has been observed that both premixed and diffusion flames exhibit either cellular or pulsating instability before extinction. Conceptually this is reasonable in that the flame is necessarily very weak in states close to extinction, while the development of instability is also favored for weak flames which are sensitive to flame temperature perturbations. The important question here is that if extinction occurs when the flame exhibits either cellular or pulsating instability, then how relevant are the predicted results on the extinction boundaries based on non-cellular and steady flames? This point was first investigated by considering the development of pulsating instability and eventual extinction of the otherwise freely-propagating planar flame with radiative heat loss. It was found that for rich hydrogen/air mixtures that with gradual increase in the equivalence ratio (ϕ), the propagation mode changes from steady, to pulsating with a single frequency, to pulsating with period doubling, and to extinction. Thus the extinction boundary should be that of the pulsating instead of the steadily propagating flame, which occur at ϕ=7.8 and 10.2 respectively. The flammable regime is therefore contracted. Furthermore, since the onset of flamefront pulsating instability occurs only for mixtures with Lewis number greater than unity, as for rich hydrogen/air and lean hydrocarbon/air (for hydrocarbons heavier than the C_2 compounds), the flammable regime for the combustion of such lean hydrocarbon fuels (e.g. propane, heptane, hexadecane) can be substantially contracted by considering, correctly, that extinction

occurs for pulsating instead of steady flames. This result is expected to be of substantial practical utility.

This work is reported in Publication No. 6.

High-Pressure Flame Structure

It was demonstrated in earlier atmospheric pressure studies by the P.I. that the flame structure as characterized by the flame thickness of a freely-standing premixed flame is basically invariant to variations in the aerodynamic strain rate κ, while that of a diffusion flame scales with κ. In the present study (Publication No. 7) this property was experimentally and computationally demonstrated to also hold for higher pressures, provided that the strain rate is density-weighted.

In a second study (Publication No. 8) the species and temperature profiles of near-sooting counterflow methane/air and propane/air diffusion flames were experimentally measured and computationally simulated, for pressures upto five atmospheres. A particularly interesting result is that the flow strain rate at the sooting limit appears to correlate well with the peak acetylene concentration for the ethylene and propane flames under all pressures studied. This demonstrates the importance of acetylene as an intermediate species in soot formation, and the potential of achieving a generalized expression for soot extinction limits.

Development of Chemical Kinetics Models

Towards the end of the present program a concerted effort was initiated toward the development of detailed and simplified chemical kinetics models for hydrocarbon oxidation. Publication Nos. 9 and 10 involve experimental and modeling studies related to the kinetics of heptane, iso-octane, and propyne, while Publication No. 12 proposes an augmented reduced mechanism (ARM), consisting of 12 lumped steps and 16 species, for methane oxidation. The performance of this ARM was evaluated by comparing its predicted results against those of the GRI-Mech from which it is derived. The comparison was conducted for a great variety of combustion phenomena, including auto and shock tube delays, well-stirred reactor responses, laminar flame speeds, and ignition-extinction responses for both premixed and diffusion flames, over extensive ranges of pressure and concentration variations. The performance has been shown to be superior.

Supersonic Combustion

The ignition in the supersonic mixing layer of hydrogen versus heated air was studied both analytically and computationally. Results show the importance of internal heating due to viscous slowdown, and the crossover temperature which defines the second explosion limit of hydrogen/oxygen oxidation.

JOURNAL PUBLICATIONS

Unsteady Flames

1. "Response of Counterflow Diffusion Flames to Oscillating Strain Rates," by H.G. Im, C.K. Law, J.S. Kim, and F.A. Williams, *Combustion and Flame*, Vol. 100, pp. 21-30 (1995).

2. "Counterflow Diffusion Flames with Unsteady Strain Rates," by H.G. Im, J.K. Bechtold, and C.K. Law, *Combustion Science and Technology*, Vol. 106, pp. 345-361 (1995).

3. "Response of Counterflow Premixed Flames to Oscillating Strain Rates," by H.G. Im, J.K. Bechtold, and C.K. Law, *Combustion and Flame*, Vol. 105, pp. 358-372 (1996).

4. "Extinction of Counterflow Diffusion Flames under Velocity Oscillations," by J.S. Kistler, C.J. Sung, T.G. Kreutz, C.K. Law, and N. Nishioka, *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 113-120 (1996).

5. "Ignition of Oscillatory Counterflowing Nonpremixed Hydrogen against Heated Air," by C. J. Sung and C.K. Law, *Combustion Science and Technology*, Vol. 129, pp. 347-360 (1997).

6. "Pulsating Instability in Near-Limit Propagation of Rich Hydrogen/Air Flames," by E.W. Christiansen, C.J. Sung, and C.K. Law, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 555-562 (1998).

High-Pressure Flame Structure

7. "Response of Counterflow Premixed and Diffusion Flames to Strain Rate Variations at Reduced and Elevated Pressures," by C.J. Sun, C.J. Sung, D.L. Zhu, and C.K. Law, *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1111-1120 (1996).

8. "Structure and Sooting Limits in Counterflow Methane/Air and Propane/Air Diffusion Flames from 1 to 5 Atmospheres," by C.J. Sung, B. Li, H. Wang, and C.K. Law, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1523-1530 (1998).

Development of Chemical Kinetics Models

9. "Laminar Flame Speed and Oxidation Kinetics of iso-Octane/Air and n-Heptane/Air Flames," S.G Davis, and C.K. Law, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 521-528 (1998).

10. "An Experimental and Kinetic Modeling Study of Propyne Oxidation," by S.G. Davis, C.K. Law, and H. Wang, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 305-312 (1998).

11. "An Augmented Reduced Mechanism for Methane Oxidation with Comprehensive Global Parametric Validation," by C.J. Sung, C.K. Law, and J.-Y. Chen, *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 295-304 (1998).

Supersonic Combustion

12. "Ignition in the Supersonic Hydrogen/Air Mixing Layer with Reduced Mechanisms," by H.G. Im, B.T. Helenbrook, S.R. Lee, and C.K. Law, *Journal of Fluid Mechanics*, Vol. 322, pp. 275-296 (1996).

13. "A Numerical Study of Ignition in the Supersonic Hydrogen/Air Laminar Mixing Layer," by M. Nishioka and C.K. Law, *Combustion and Flame*, Vol. 108, pp. 199-219 (1997).

Additional Topics of Investigation

14. "A Flame-Controlling Continuation Method for Generating S-Curve Responses with Detailed Chemistry," by M. Nishioka, C.K. Law, and T. Takeno, *Combustion and Flame*, Vol. 104, pp. 328-342 (1996).

15. "Further Studies on Effects of Thermophoresis on Seeding Particles in Measurements of Strained Flames," by C.J. Sung, J.S. Kistler, M. Nishioka, and C.K. Law, *Combustion and Flame*, Vol. 105, pp. 189-201 (1996).

16. "Structure and Propagation of Premixed Flame in Nozzle-Generated Counterflow," by B.H. Chao, F.N. Egolfopoulos, and C.K. Law, *Combustion and Flame*, Vol 109, pp. 620-638 (1997).

Review Articles

17. "The Role of Chain Mechanisms in Some Fundamental Combustion Phenomena," by C.K. Law, *Physical and Chemical Aspects of Combustion: A Tribute to Irvin Glassman, Combustion Science and Technology Book Series*, Vol. 4 (Eds.: F.L. Dryer and R.F. Sawyer), Gordon and Breach, pp. 3-27 (1997).

18. "On the Aerodynamics of Flame Surfaces," by C.K. Law, C.J. Sung, and C.J. Sun, *Annual Review of Heat Transfer*, Vol. VIII, (Ed.: C.-L. Tien), Begell House, pp. 93-151 (1997).

PREPRINTS AND REPORTS

1. "Counterflow Diffusion Flame with Unsteady Strain Rates," by H.G. Im, J.K. Bechtold, and C.K. Law, AIAA-95-0128, 33rd Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.

2. "On the Structural Response of Counterflow Diffusion Flames to Strain Rate Variations," by C.J. Sung, J.B. Liu, and C.K. Law, AIAA-95-0129, 33rd Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.

3. "A Numerical Study of Ignition in the Supersonic Hydorgen/Air Laminar Mixing Layer," by M. Nishioka and C.K. Law, AIAA-95-0377, 33rd Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.

4. "Laminar Burning Rates and Oxidation Kinetics of Premixed Benzene/Air and Toluene/Air Flames," by S.G. Davis, K. Brezinsky, and C.K. Law, Paper No. 95S-048, Joint Technical Meeting of the Central and Western States Section, the Combustion Institute, San Antonio, Texas, April 23-26, 1995.

5. "On the Structure of Counterflow Ethylene/Oxygen/Nitrogen Diffusion Flames," by C.J. Sun, C.J. Sung, H. Wang, and C.K. Law, Paper No. 95S-086, Joint Technical Meeting of the Central and Western States Section, the Combustion Institute, San Antonio, Texas, April 23-26, 1995.

6. "On the Extinction of Counterflow Diffusion Flames under Oscillation," by J. S. Kistler, C.J. Sung, T.G. Kreutz, C.K. Law, and M. Nishioka, Paper No. 48, Technical Meeting of the Eastern States Section of the Combustion Institute, Worcester, MA, Oct. 16-18, 1995.

7. "On the Oxidation Kinetics of Premixed Benzene/Air and Toluene/Air Flames," by S.G. Davis, H. Wang, K. Brezinsky and C.K. Law, Paper No. 83, Technical Meeting of the Eastern States Section of the Combustion Institute, Worcester, MA, Oct. 16-18, 1995.

8. "On the Structure of Non-Sooting Counterflow Acetylene and Ethylene Diffusion Flames," by C.J. Sun, H. Wang, C.J. Sung, and C.K. Law, Paper No. 8, Technical Meeting of the Eastern States Section of the Combustion Institute, Worcester, MA, Oct. 16-18, 1995.

9. "On the Extinction of Counterflow Diffusion Flames in an Oscillating Flow Field," by J.S. Kistler, T.G. Kreutz, C.J. Sung, and C.K. Law, AIAA Paper No. 96-0217, 34th Aerospace Sciences Meeting, Reno, NV, Jan. 15-18, 1996.

10. "Structural Response and Extinction of Counterflow Premixed and Diffusion Flames under Velocity Oscillations," by C.J. Sung and C.K. Law, Paper No. 78, Technical Meeting of the Central States Section of the Combustion Institute, St. Louis, MO, May 5-7, 1996.

11. "Extinction of Ultra-Weak Stretched Flames and Extended Limits of Flammability," by C.J. Sung and C.K. Law, Paper No. 82, Technical Meeting of the Central States Section of the Combustion Institute, St. Louis, MO, May 5-7, 1996.

12. "Unsteady Ignition of Nonpremixed Counterflowing Hydrogen versus Heated Air," by C.J. Sung and C.K. Law, Paper No. 6, Technical Meeting of the Eastern States Section of the Combustion Institute, Hilton Head, SC, Dec. 9-11, 1996.

13. "Pulsating Instability in the Fundamental Flammability Limits of Rich Hydrogen/Air Flames," by E. W. Christiansen, C. J. Sung, and C. K. Law, Paper No. 97S-023, Spring Tech. Meeting of the Western States Section of the Combustion Insitute, Sandia National Laboratories, Livermore, CA, April 14-15, 1997.

14. "Pulsating Instability and Flammability Limits of One-Dimensional Planar Flames with One-Step Chemistry and Constant Properties," by E. W. Christiansen, C. J. Sung, C. J. Sun, and C. K. Law, Paper No. 90, Tech. Meeting of the Eastern States Section, the Combustion Institute, Hartford, CT, Oct. 27-29, 1997.

15. "Aerodynamics of Flames," by C.K. Law, Fourth Asian Pacific International Symposium on Combustion and Energy Utilization, Bangkok, Thailand, December 8-11, 1997. **Keynote Paper**

16. "Structural Sensitivity, Response and Extinction of Unsteady Counterflow Flames," by C.J. Sung and C.K. Law, AIAA Paper No. 98-0555, 36th Aerospace Sciences Meeting, Reno, NV, January 12-15, 1998.

17. "Influence of Chemical Kinetics in the Self-Ignition of Nonpremixed Supersonic Hydrogen-Air Flows," by C.J. Sung, J.G. Li, G. Yu, and C.K. Law, AIAA Paper No. 98-0722, 36th Aerospace Sciences Meeting, Reno, NV, January 12-15, 1998.

PRESENTATIONS

Keynote and Named Lectures

1. "The Role of Chemistry in Combustion," and "The Role of Aerodynamics in Combustion," College of Engineering, Universityof Illinois, Chicago, IL, Nov. 3-5, 1997. **Paul M. Chung Distinguished Lecture Series**

2. "Aerodynamics of Flames," Fourth Asian-Pacific International Symposium on Combustion and Energy Utilization, Bangkok, Thailand, December 8-11, 1997. **Keynote Lecture**

Invited Departmental Seminars

1. "Some Recent Contributions in Flame and Spray Processes," NIST, March 7, 1995.

2. "Coupling Chemistry and Transport in Combustion Phenomena," Department of Mechanical Enginering, University of California, Berkeley, CA, March 13, 1995.

3. "Some Recent Contributions in Flame and Spray Phenomena," Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, April 4, 1995.

4. "On the Structure and Response of Stretched Premixed Flames," Department of Mechanical Engineering, Washington State University, Pullman, WA, Aug. 15, 1995.

5. "Realistic and Efficient Chemical Kinetic Mechanisms in Combustion Modeling," Air Force/NASA Workshop on Supersonic Combustion, Newport News, VA, June 14-16, 1996.

6. "Towards Quantitative Description of Laminar Flamelets," Technical University of Eindhoven, Eindhoven, The Netherlands, Jan. 27, 1997.

7. "The Role of Aerodynamics in Combustion," Institute of Mechanics, Chinese Academy of Sciences, Beijing, China, June 23, 1997.

8. "The Role of Chemistry in Combustion," Institute of Mechanics, Chinese Academy of Sciences, Beijing, China, June 23, 1997.

9. "Forced and Intrinsic Unsteady Flame Phenomena," Turbulent Combustion Workshop, Sandia National Laboratories, Livermore, CA, August 18-21, 1997.

10. "Aerodynamics of Laminar Premixed Flames," Department of Mechanical Engineering, the University of Michigan, Ann Arbor, MI, September 19, 1997.

Contributed Presentations

1. "On the Structural Response of Counterflow Diffusion Flames to Strain Rate Variations," 33rd Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.

2. "Laminar Burning Rates and Oxidation Kinetics of Premixed Benzene/Air and Toluene/Air Flames," Joint Tech. Meeting of the Central and Western States Sections of the Combustion Institute, San Antonio, TX, April, 23-26, 1995.

3. "On the Evolution of Two-Dimensional Flame Surfaces," 34th Aerospace Science Meeting, Reno, NJ, Jan. 15-18, 1996.

4. "On the Extinction of Counterflow Diffusion Flames in an Oscillating Flow Field," 34th Aerospace Sciences Meeting, Reno, NV, Jan. 15-18, 1996.

5. "Pulsating Instability in the Fundamental Flammability Limits of Rich Hydrogen/Air Flames," Spring Tech. Meeting of the Western States Section of the Combustion Institute, Sandia Laboratories, Livermore, CA, April 14-15, 1997.

PERSONNEL

Principal Investigator

C.K. Law

Faculty Collaborators

J.K. Bechtold (New Jersey Institute of Technology)

B.H. Chao (Hawaii)

J.Y. Chen (Berkeley)

F.N. Egolfopoulos (USC)

T. Takeno (Nagoya)

H. Wang (Delaware)

F.A. Williams (UCSD)

Senior Collaborators

H.G. Im (Stanford and Sandia)

J.S. Kim (Korea Institute of Science and Technology)

S.R. Lee (Korea National University)

Post-Doctoral Fellows and Research Staff

T.G. Kreutz

B. Li

N. Nishioka

C.J. Sung

D.L. Zhu

Graduate Students

E.W. Christiansen (Ph. D. Candidate)

S.G. Davis (Ph. D., 1998)

B.T. Helenbrook (Ph. D., 1998)

J.S. Kistler (MSE, 1995)

C.J. Sun (Ph. D., 1998)

SIGNIFICANT INTERACTIONS

Contact: Allison Engine Company, M. S. Anand, (317) 230-2828

Results: Use of comprehensively-validated reduced chemical kinetic mechanism allows improved description of complex species and velocity fields.

Applications: Realistic simulation of combustors, especially predictions of pollutant formation.

Principal Investigator Annual Data Collection (PIADC) Survey Form

NOTE: If there is insufficient space on this survey to meet your data submissions, please submit additional data in the same format as identified below.

PI DATA

Name (Last, First, MI) Law, Chung K.

Institution Princeton University

Contract/Grant No. F49620-95-1-0092

AFOSR USE ONLY
Project/Subarea
_____/_____

NX _____

FY _____

NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty: 2 Post Doctorates 3 Graduate Students 3 Other _____

PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

NOTE: List names in the following format: Last Name, First Name, MI

Include: Articles on peer reviewed publications, journals, book chapters, and editorships of books

Do Not Include: Unreviewed proceedings and reports, abstracts. "Scientific American" type articles, or articles that are not primary reports of new data and articles submitted or accepted for publication, but with a publication date outside the stated time frame.

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: Response of Counterflow Diffusion Flames to Oscillating Strain Rates

Authors: H. G. Im, C. K. Law, J. S. Kim, and F. A. Williams

Publisher (if applicable) _____

Volume: 100 Page(s): 21-30 Month Published: _____ Year Published: 1995

Name of Journal, Book, etc. *Combustion Science and Technology*

Title of Article: Counterflow Diffusuion Flames with Unsteady Strain Rates

Authors: H. G. Im, J. K. Bechtold, and C. K. Law

Publisher (if applicable) _____

Volume: 106 Page(s): 345-361 Month Published: _____ Year Published: 1995

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: Response of Counterflow Premixed Flames to Oscillating Strain Rates

Authors: H. G. Im, J. K. Bechtold, and C. K. Law

Publisher (if applicable) _____

Volume: 105 Page(s): 358-372 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute

Title of Article: Response of Counterflow Premixed and Diffusion Flames to Strain Rate Variations at Reduced and Elevated Pressures

Authors: C. J. Sun, C. J. Sung, D. L. Zhu, and C. K. Law

Publisher (if applicable) _____

Volume: _____ Page(s): 1111-1120 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute

Title of Article: Extinction of Counterflow Diffusion Flames under Velocity Oscillations

Authors: J. S. Kistler, C. J. Sung, T. G. Kreutz, C. K. Law, and N. Nishioka

Publisher (if applicable) _____

Volume: _____ Page(s): 113-120 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Combustion Science and Technology*

Title of Article: Ignition of Oscillatory Counterflow Nonpremixed Hydrogen against Heated Air

Authors: C. J. Sung, and C. K. Law

Publisher (if applicable) _____

Volume: 129 Page(s): 347-360 Month Published: _____ Year Published: 1997

Name of Journal, Book, etc. *Twenty-Seventh Symposium (International) on Combustion,* The Combustion Institute

Title of Article: Pulsating Instability in Near-Limit Propagation of Rich Hydrogen/Air Flames

Authors: E. W. Christiansen, C. J. Sung, and C. K. Law

Publisher (if applicable) _____

Volume: _____ Page(s): 555-562 Month Published: _____ Year Published: 1998

Name of Journal, Book, etc. *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute

Title of Article: Structure and Sooting Limits in Counterflow Methane/Air and Propane/Air Diffusion Flames from 1 to 5 Atmospheres

Authors: C. J. Sung, B. Li, H. Wang, and C. K. Law

Publisher (if applicable) _____

Volume: _____ Page(s): 1523-1530 Month Published: _____ Year Published: 1998

Name of Journal, Book, etc. *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute

Title of Article: Laminar Flame Speed and Oxidation Kinetics of iso-Octane/Air and n-Heptane/Air Flames

Authors: S. G. Davis and C. K. Law

Publisher (if applicable) _____

Volume: _____ Page(s): 521-528 Month Published: _____ Year Published: 1998

Name of Journal, Book, etc. *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute

Title of Article: An Experimental and Kinetic Modeling Study of Propyne Oxidation

Authors: S. G. Davis, C. K. Law, and H. Wang

Publisher (if applicable) _____

Volume: _____ Page(s): 305-312 Month Published: _____ Year Published: 1998

Name of Journal, Book, etc. *Twenty-Seventh Symposium (International) on Combustion*, The Combustion Institute

Title of Article: An Augmented Reduced Mechanism for Methane Oxidation with Comprehensive Global Parametric Validation

Authors: C. J. Sung, C. K. Law, and J.-Y. Chen

Publisher (if applicable) _____

Volume: _____ Page(s): 295-304 Month Published: _____ Year Published: 1998

Name of Journal, Book, etc. *Journal of Fluid Mechanics*

Title of Article: Ignition in the Supersonic Hydrogen/Air Mixing Layer with Reduced Mechanisms

Authors: H. G. Im, B. T. Helenbrook, S. R. Lee, and C. K. Law

Publisher (if applicable) _____

Volume: 322 Page(s): 275-296 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: A Numerical Study of Ignition in the Supersonic Hydrogen/Air Laminar Mixing Layer

Authors: M. Nishioka and C. K. Law

Publisher (if applicable) _____

Volume: 108 Page(s): 199-219 Month Published: _____ Year Published: 1997

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: A Flame-Controlling Continuation Method for Generating S-Curve Responses with Detailed Chemistry

Authors: M. Nishioka, C. K. Law, and T. Takeno

Publisher (if applicable) _____

Volume: 104 Page(s): 328-342 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: Further Studies on Effects of Thermophoresis on Seeding Particles in Measurements of Strained Flames

Authors: C. J. Sung, J. S. Kistler, M. Nishioka, and C. K. Law

Publisher (if applicable) _____

Volume: 105 Page(s): 189-201 Month Published: _____ Year Published: 1996

Name of Journal, Book, etc. *Combustion and Flame*

Title of Article: Structure and Propagation of Premixed Flame in Nozzle-Generated Counterflow

Authors: B. H. Chao, F. N. Egolfopoulos, and C. K. Law

Publisher (if applicable) _____

Volume: 109 Page(s): 620-638 Month Published: _____ Year Published: 1997

Name of Journal, Book, etc. *Physical and Chemical Aspects of Combustion: A Tribute to Irvin Glassman, Combustion Science and Technology Book Series*

Title of Article: The Role of Chain Mechanisms in Some Fundamental Combustion Phenomena

Authors: Chung K. Law

Publisher (if applicable) Gordon and Breach (Eds.: F. L. Dryer and R. F. Sawyer)

Volume: 4 Page(s): 3-17 Month Published: _____ Year Published: 1997

Name of Journal, Book, etc. *Annual Review of Heat Transfer*

Title of Article: On the Aerodynamics of Flame Surfaces

Authors: C. K. Law, C. J. Sung, and C. J. Sun

Publisher (if applicable) Begell House (Ed.: C.-L. Tien)

Volume: VIII Page(s): 93-151 Month Published: _____ Year Published: 1997

HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Include: All honors and awards received during the lifetime of the contract or grant, and any life achievement honors such as (Nobel prize, honorary doctorates, and society fellowships) prior to this contract or grant.

Do Not Include: Honors and awards unrelated to the scientific field covered by the contract/grant.

Honor/Award: Fellow Year Received: 1989

Honor/Award Recipient(s): C. K. Law

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13. ABSTRACT *(Maximum 200 words)*

The objective of the present program was to study the structure and response of laminar premixed and nonpremixed flames with emphases on effects of high pressure, flame/flow unsteadiness, and chemistry. The investigations were conducted through laser-based experimentation, computational simulation with detailed chemistry and transport descriptions, and advanced mathematical analysis. Specific phenomena studied include the steady-state structure, burning rate, and extinction of flames, the response to impulsive and periodic flow field strain rate variations, the development of intrinsic flamefront pulsating instability and its relation to extinction, and studies related to the development of detailed and simplified chemical kinetic mechanisms. These results are expected to be useful to the general interests of AFOSR in the fundamental and practical issues of flame dynamics and chemical kinetics, turbulent combustion, soot formation, radiative hear transfer, flame extinction, stabilization, flammability, and supersonic combustion.

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